

Issues in Integrated Transport Codes

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Contents

- TASK: **T**ransport **A**nalysing **S**ystem for tokama**K**
- TASK/TR: Diffusive Transport Simulation
- TASK/TX: Dynamical Transport Simulation
- TASK2005: Documentation
- Summary

TASK Code

- **Transport Analysing System for TokamaK**
- **Features**
 - **A Core of Integrated Modelling Code in BPSI**
 - Modular Structure
 - Reference Data Interface
 - **Various Heating and Current Drive Scheme**
 - EC, LH, IC, AW, (NB)
 - **High Portability**
 - Most of Library Routines Included (except LAPACK and MPI)
 - Own Graphic Libraries (gsaf, gsgl)
 - **Development using CVS** (Concurrent Version System)
 - Open Source (by the end of 2004)
 - **Parallel Processing using MPI Library**
 - **Extension to Toroidal Helical Plasmas**

Modules of TASK

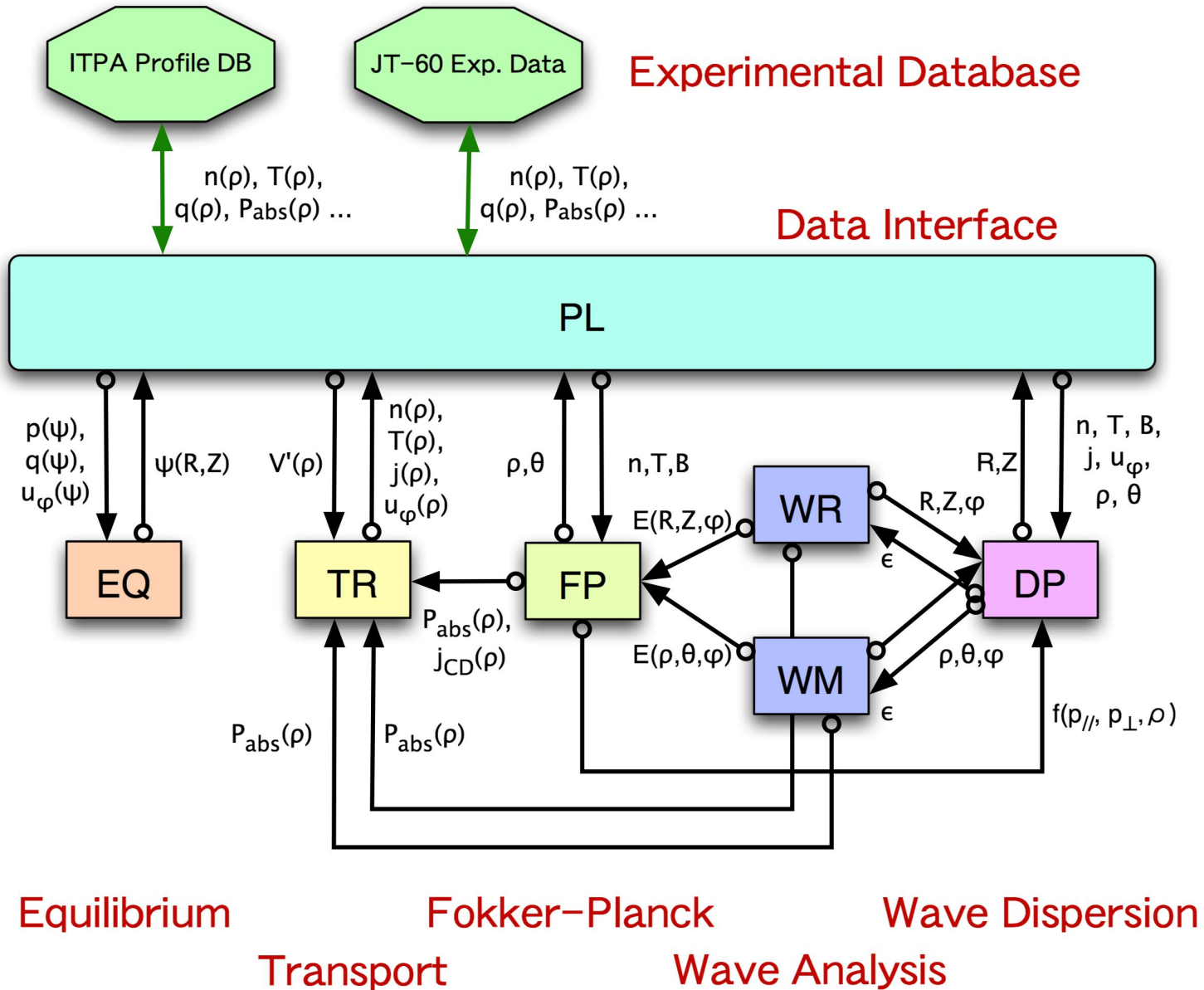
EQ	2D Equilibrium	Fixed boundary, Toroidal rotation
TR	1D Transport	Diffusive Transport, Transport models
WR	3D Geometr. Optics	EC, LH: Ray tracing, Beam tracing
WM	3D Full Wave	IC, AW: Antenna excitation, Eigen mode
FP	3D Fokker-Planck	Relativistic, Bounce-averaged
DP	Wave Dispersion	Local dielectric tensor, Arbitrary $f(\mathbf{v})$
PL	Data Interface	Data conversion, Profile database
LIB	Libraries	

Associated Libraries

GSAF	2D Graphic library for X Window and EPS
GSGL	3D Graphic library using OpenGL

All developed in Kyoto U

Original Structure of TASK



Under Development

- **New Modules**

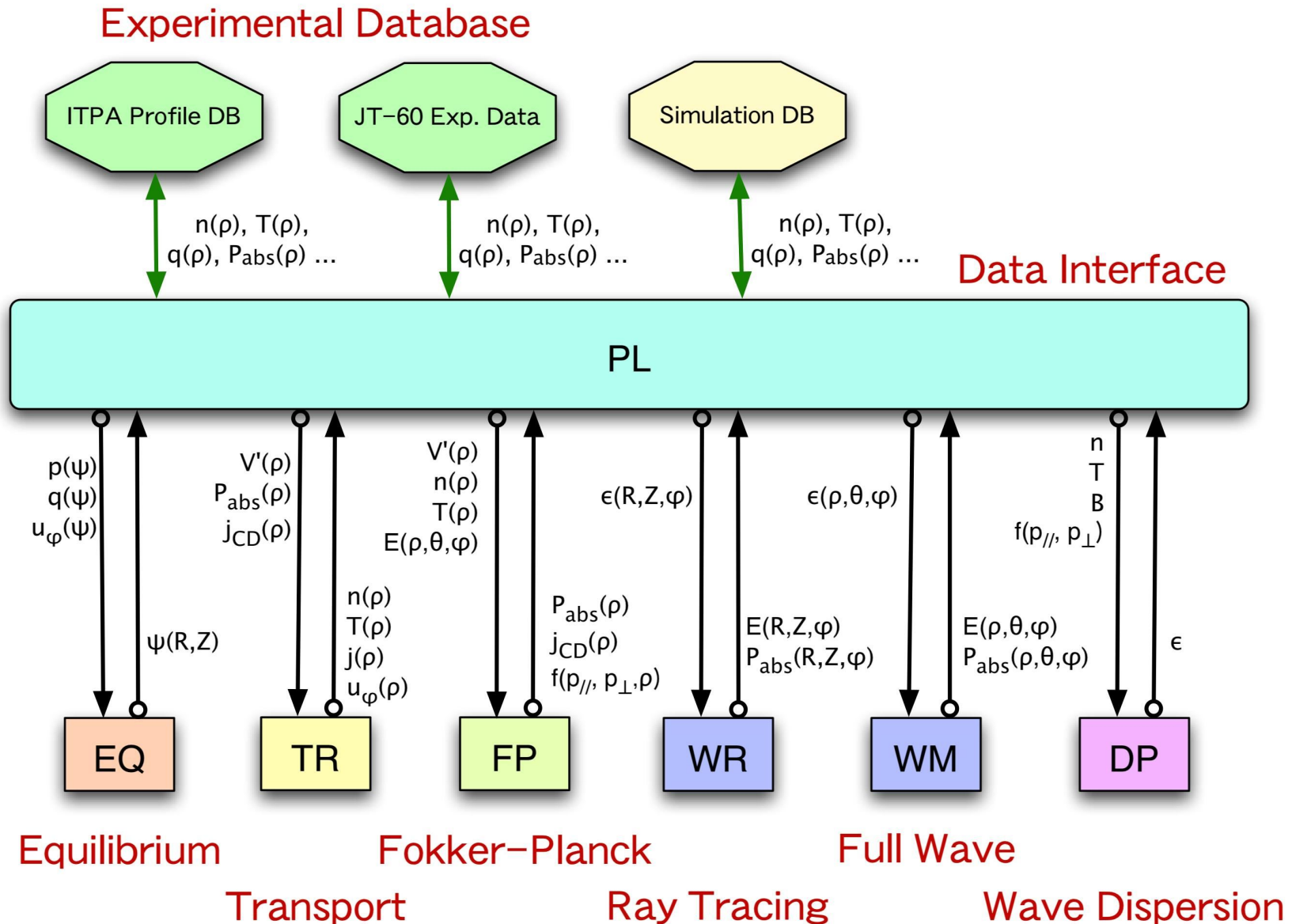
- **EX**: 2D equilibrium with free boundary
- **TX**: Transport analysis based on flux-averaged fluid equation
- **WA**: Global linear stability analysis
- **WI**: Integro-differential wave analysis (FLR, $k \cdot \nabla B \neq 0$)

- **Extension to 3D Helical System**

- **3D Data Structure**
- **3D Equilibrium**: VMEC, HINT
- **Wave Analysis**: Already 3D
- **Transport Analysis**: New transport model

- **New Modular Structure**

New Modular Structure of TASK



Transport Analysis

- **Level of Analysis:**
 - **TASK/TR**: Diffusive transport equation:
 - Flux-Gradient relation
 - Conventional transport analysis
 - **TASK/TX**: Dynamical transport equation:
 - Flux-averaged fluid equation
 - Plasma rotation and transient phenomena
 - **TASK/FP**: Kinetic transport equation:
 - Bounce-averaged Fokker-Plank equation
 - Modification of momentum distribution

Diffusive Transport Analysis: TASK/TR

- **Transport Equation Based on Gradient-Flux Relation**
 - **Multi thermal species**: e.g. Electron, D, T, He
 - Density, thermal energy, (toroidal rotation)
 - **Two beam components**: Beam ion, Energetic α
 - Density, toroidal rotation
 - **Neutral**: Two component (cold and hot), Diffusion equation
 - **Impurity**: Thermal species or fixed profile
- **Transport Model**
 - **Neoclassical**: Wilson, Hinton & Hazeltine, Sauter, NCLASS
 - **Turbulent**: CDBM (current diffusive ballooning mode), GLF23 (V1.61), IFS/PPPL, Weiland
- **Interface to Experimental Data**
 - UFILE (ITPA profile DB)

Turbulent Transport Model

- **Development of Robust Transport Model**
 - **L-mode confinement time scaling**
 - **Large transport near the plasma edge in L-mode**
 - **H-mode confinement time scaling for given edge temperature**
 - **Formation of internal transport barrier**
 - **Experimentally observed profile**
 - **Behavior of fluctuation**
- **Validation of the Model**
 - **Profile Database (ITPA)**
 - **Large-scale Turbulence Simulation**

CDBM Turbulence Model

- **Marginal Stability Condition** ($\gamma = 0$)

$$\chi_{\text{TB}} = F(s, \alpha, \kappa, \omega_{E1}) \alpha^{3/2} \frac{c^2}{\omega_{pe}^2} \frac{v_A}{qR}$$

Magnetic shear $s \equiv \frac{r}{q} \frac{dq}{dr}$

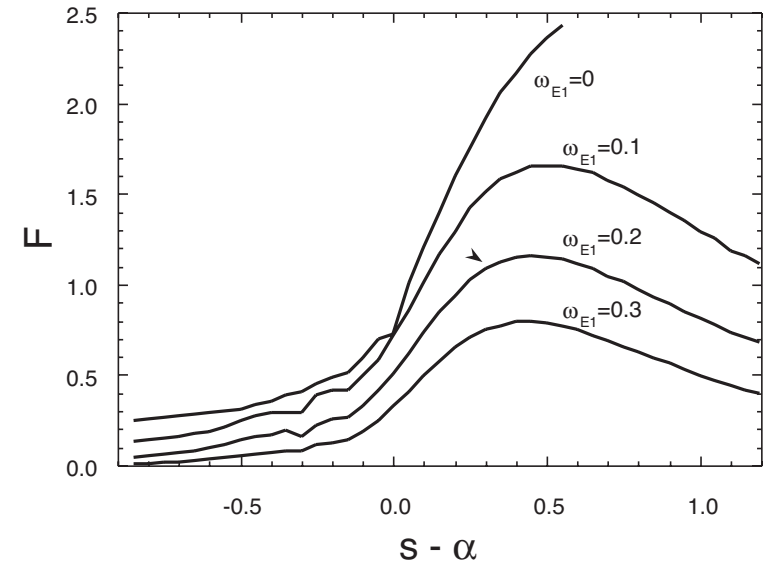
Pressure gradient $\alpha \equiv -q^2 R \frac{d\beta}{dr}$

Magnetic curvature $\kappa \equiv -\frac{r}{R} \left(1 - \frac{1}{q^2}\right)$

$E \times B$ rotation shear $\omega_{E1} \equiv \frac{r^2}{sv_A} \frac{d}{dr} \frac{E}{rB}$

- **Weak and negative magnetic shear, Shafranov shift and $E \times B$ rotation shear**
reduce thermal diffusivity.

$s - \alpha$ dependence of $F(s, \alpha, \kappa, \omega_{E1})$



Fitting Formula

$$F = \begin{cases} \frac{1}{1 + G_1 \omega_{E1}^2} \frac{1}{\sqrt{2(1 - 2s')(1 - 2s' + 3s'^2)}} & \text{for } s' = s - \alpha < 0 \\ \frac{1}{1 + G_1 \omega_{E1}^2} \frac{1 + 9\sqrt{2}s'^{5/2}}{\sqrt{2(1 - 2s' + 3s'^2 + 2s'^3)}} & \text{for } s' = s - \alpha > 0 \end{cases}$$

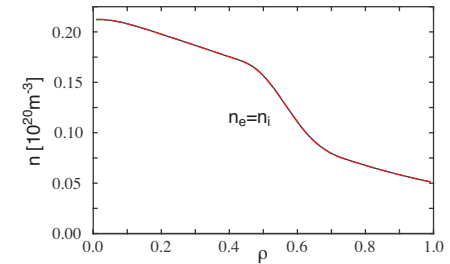
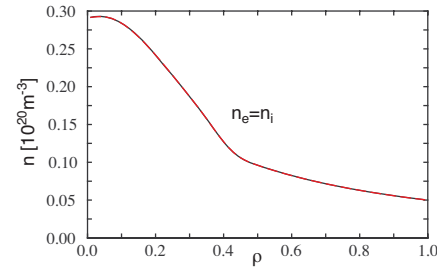
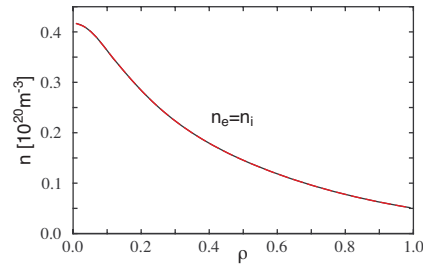
Typical Profile (CDBM+NCLASS)

L-mode

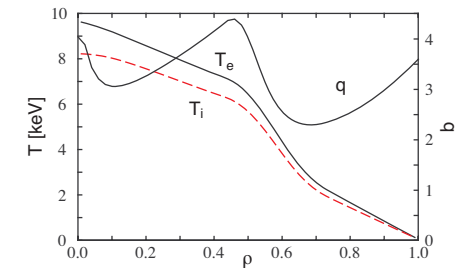
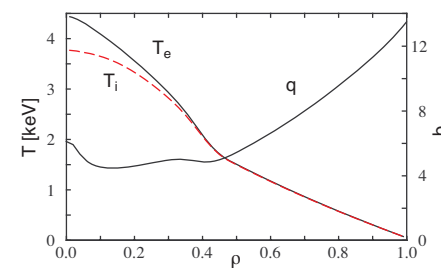
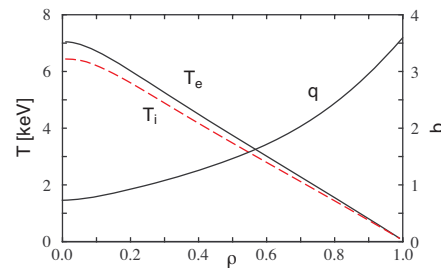
High β_p

Reversed shear

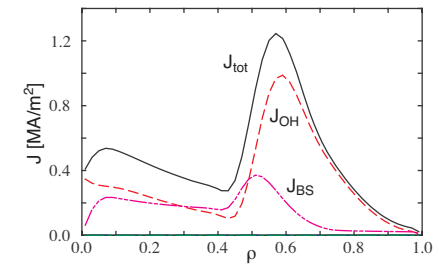
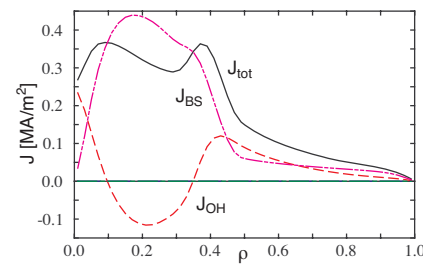
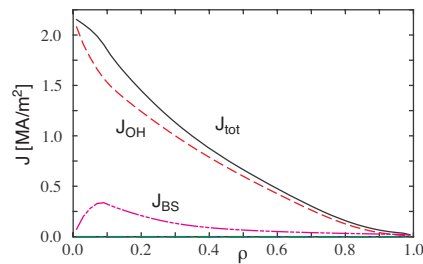
$n(\rho)$



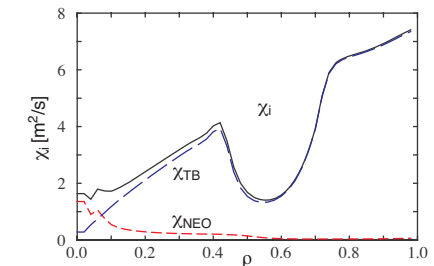
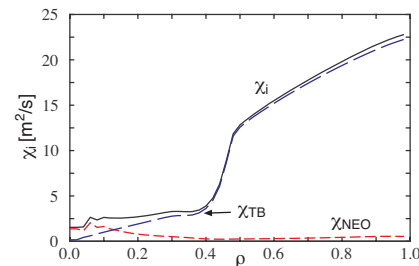
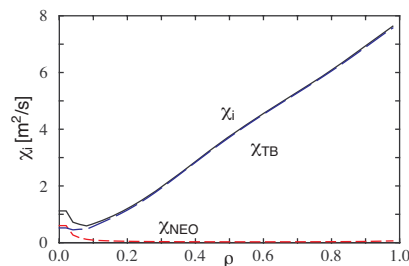
$T(\rho), q(\rho)$



$j(\rho)$



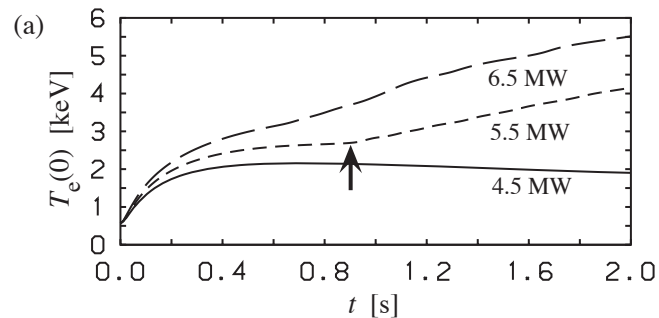
$\chi_i(\rho)$



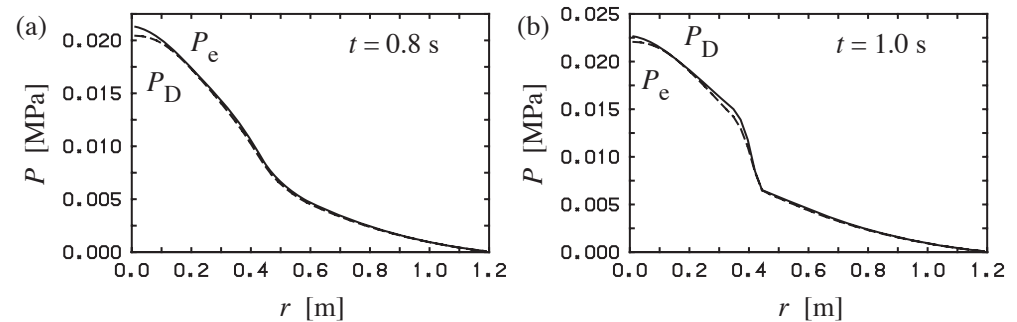
Effect of $E \times B$ Rotation Shear

- **Reduction of transport** due to small s and large α : $F(s, \alpha, \kappa)$
 - \implies **Rapid increase of rotation shear**: $1/[1 + G(s, \alpha)\omega_{E1}^2]$
 - \implies **Transition to enhanced ITB**

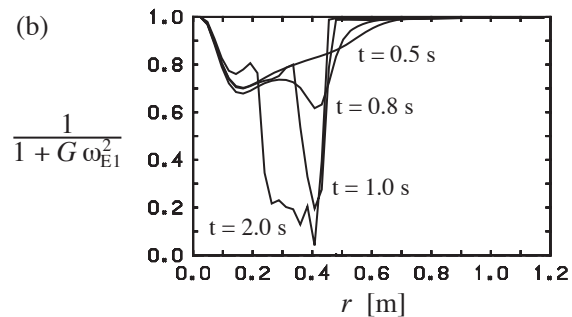
Time evolution of $T_e(0)$



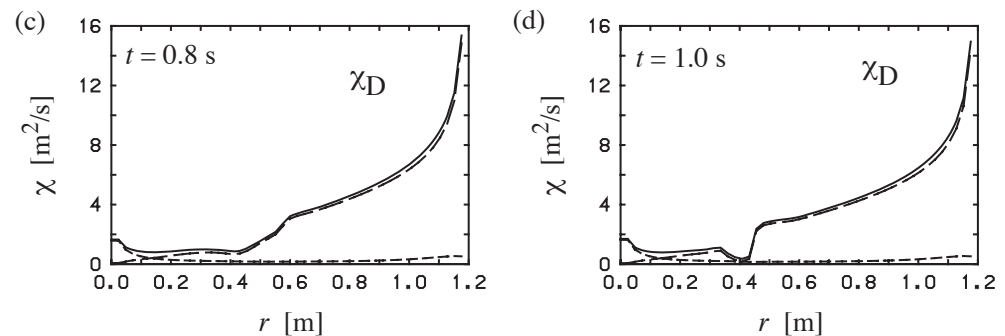
Pressure Profile Before and After Transition



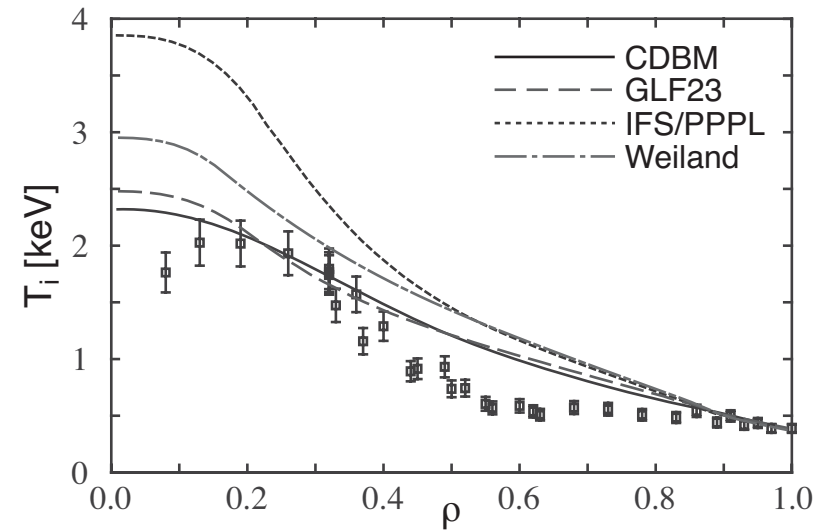
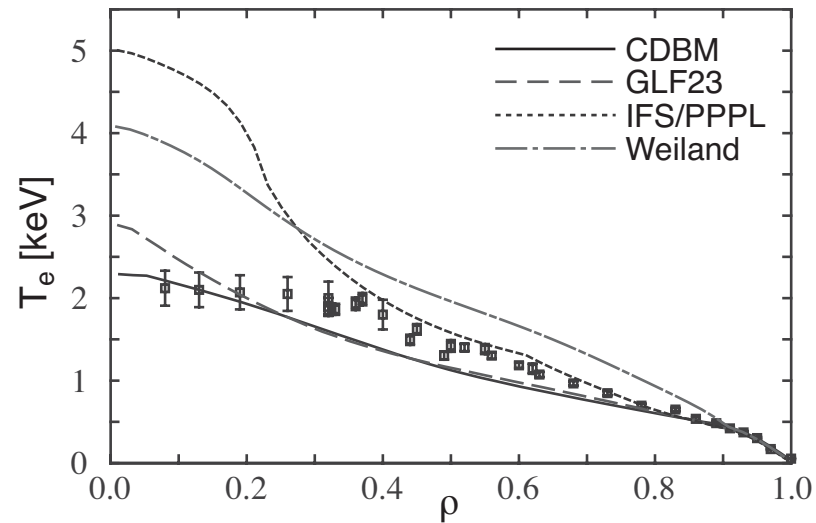
Rapid Change of Rotation Shear



Thermal Diffusivity Before and After Transition



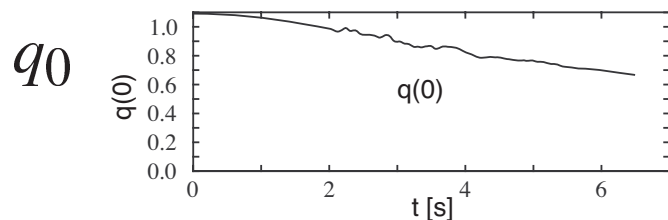
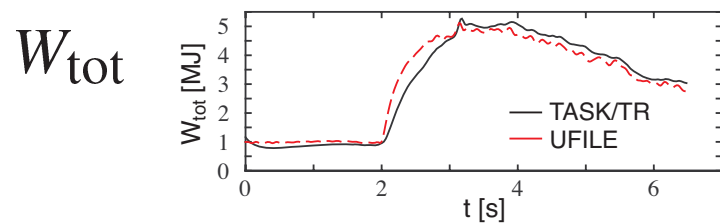
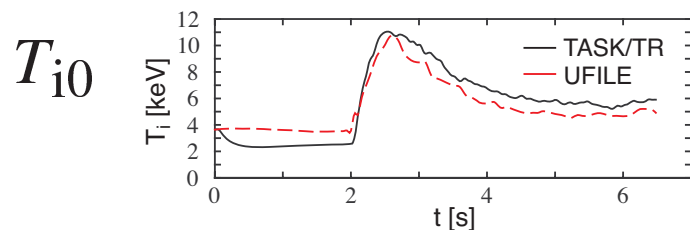
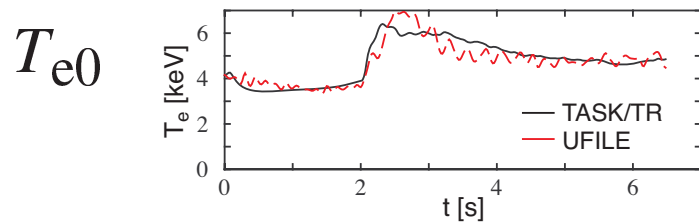
Heat transport simulation for the L-mode shot #82188 on DIII-D tokamak



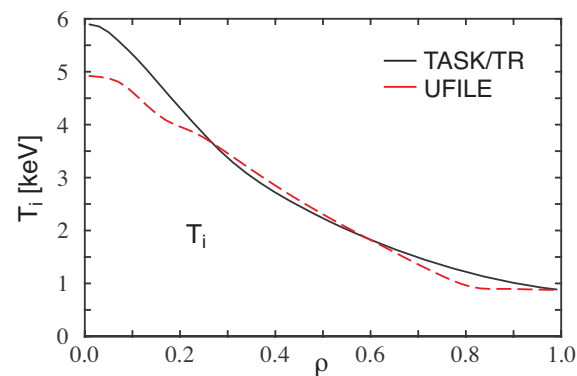
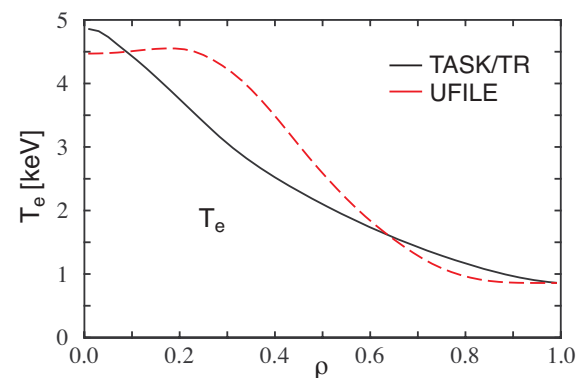
- Incidental agreement of CDBM and GLF23 results
- Fairly good agreement with experiments

Comparison with JET Experiment

- Shot number: 19691



T_e and T_i



- Sawtooth relaxation slightly improves T_e profile.

Comparison with JT-60 Experiment

- **Reversed Shear Configuration**

- **Shot number: 29728**

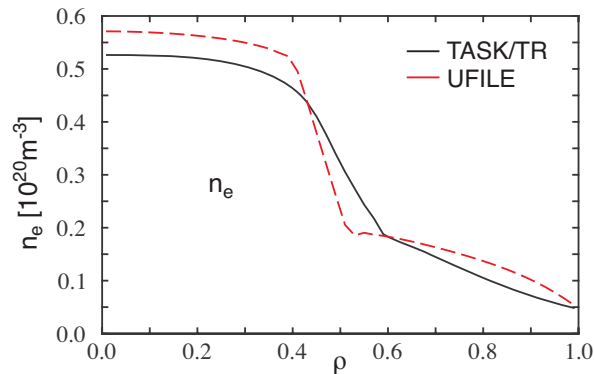
- Profiles q , P_e , P_i : given

- Metric data: given

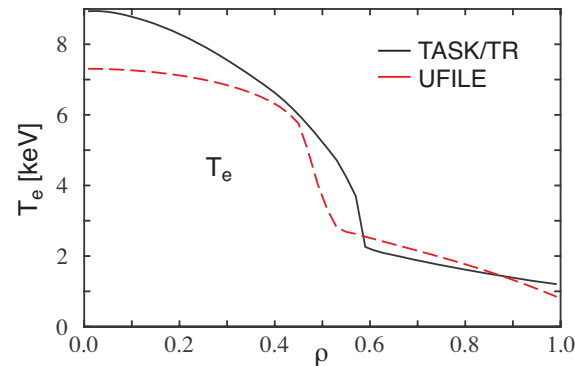
- Edge density and temperature: given

- Transport model: Sauter + CDBM(with $E \times B$ rotation)

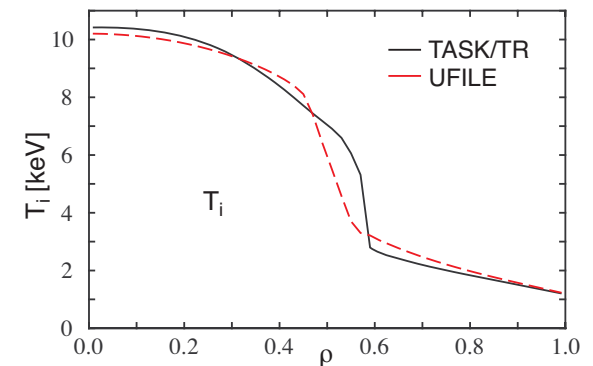
$n_e(\rho)$



$T_e(\rho)$

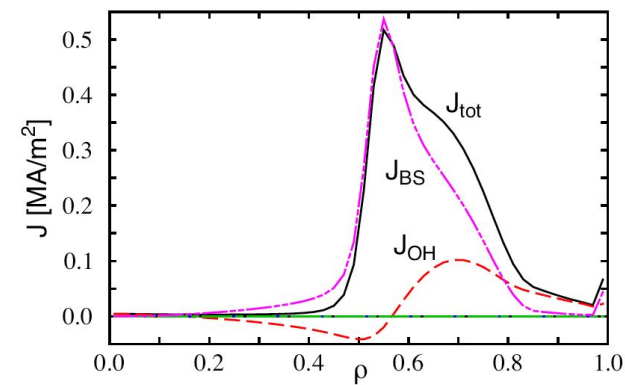
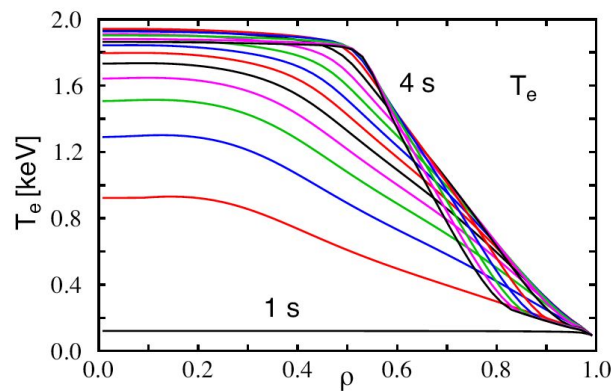
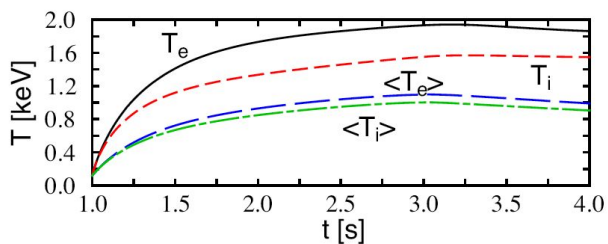
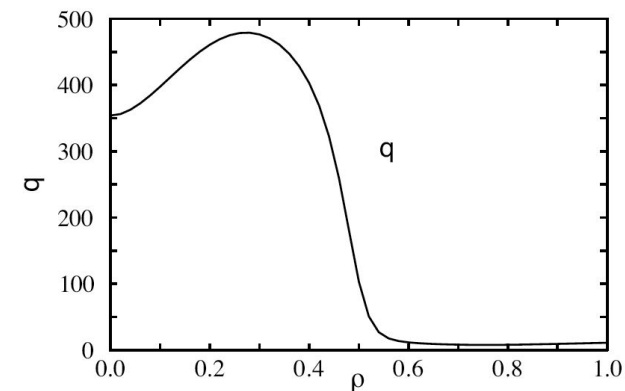
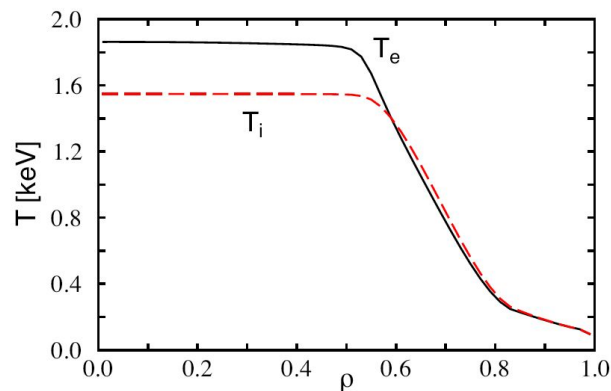
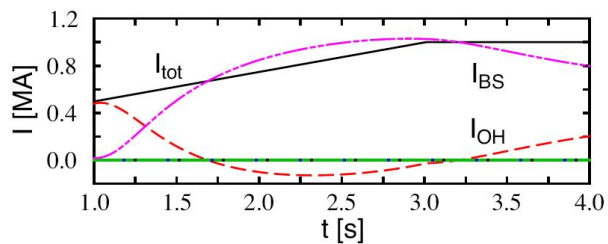


$T_i(\rho)$



Simulation of Current Hole Formation

- Current ramp up: $I_p = 0.5 \rightarrow 1.0$ MA
- Moderate heating: $P_H = 6.5$ MW
- **Current hole** is formed.



Modeling of ETB Formation

- **Transport Simulation including Core and SOL Plasmas**
- **Role of Separatrix**
 - Closed magnetic surface \iff Open magnetic field line
 - Difference of dominant transport process
- **Radial Electric Field**
 - Poloidal rotation, Toroidal rotation
 - Polarization current
 - Poisson equation
- **Atomic Processes**
 - Ionization, Charge exchange, Recycling

Dynamical Transport Model: TASK/TX

- **1D Transport code** (TASK/TX) *Ref. Fukuyama et al.*
- **Two fluid equation for electrons and ions**
 - Flux surface average
 - Coupled with Maxwell equation
 - Neutral diffusion equation
- **Neoclassical transport**
 - Included as a poloidal viscosity term
 - Diffusion, resistivity, bootstrap current, Ware pinch
- **Anomalous transport**
 - Current diffusive ballooning mode
 - Ambipolar diffusion through poloidal momentum transfer
 - Perpendicular viscosity

Model Equation (1)

- **Fluid equations** (electrons and ions)

$$\frac{\partial n_s}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} (r n_s u_{sr}) + S_s$$

$$\frac{\partial}{\partial t} (m_s n_s u_{sr}) = -\frac{1}{r} \frac{\partial}{\partial r} (r m_s n_s u_{sr}^2) + \frac{1}{r} m_s n_s u_{s\theta}^2 + e_s n_s (E_r + u_{s\theta} B_\phi - u_{s\phi} B_\theta) - \frac{\partial}{\partial r} n_s T_s$$

$$\frac{\partial}{\partial t} (m_s n_s u_{s\theta}) = -\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 m_s n_s u_{sr} u_{s\theta}) + e_s n_s (E_\theta - u_{sr} B_\phi) + \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^3 n_s m_s \mu_s \frac{\partial u_{s\theta}}{\partial r} \frac{u_{s\theta}}{r} \right)$$

$$-v^{\text{NC}} m_s n_s u_{s\theta} - \sum_{s'} v_{ss'}^{\text{C}} m_s n_s (u_{s\theta} - u_{s'\theta}) + F_{s\theta}^{\text{W}} - v_s^{\text{CX}} m_s n_s u_{s\theta} - v_s^{\text{L}} m_s n_s u_{s\theta}$$

$$\frac{\partial}{\partial t} (m_s n_s u_{s\phi}) = -\frac{1}{r} \frac{\partial}{\partial r} (r m_s n_s u_{sr} u_{s\phi}) + e_s n_s (E_\phi + u_{sr} B_\theta) + \frac{1}{r} \frac{\partial}{\partial r} \left(r n_s m_s \mu_s \frac{\partial u_{s\phi}}{\partial r} \right)$$

$$-v^{\text{NC}} m_s n_s u_{s\phi} - \sum_{s'} v_{ss'}^{\text{C}} m_s n_s (u_{s\phi} - u_{s'\phi}) + F_{s\phi}^{\text{W}} - v_s^{\text{CX}} m_s n_s u_{s\phi} - v_s^{\text{L}} m_s n_s u_{s\phi}$$

$$\frac{\partial}{\partial t} \frac{3}{2} n_s T_s = -\frac{1}{r} \frac{\partial}{\partial r} r \left(\frac{5}{2} u_{sr} n_s T_s - n_s \chi_s \frac{\partial T_e}{\partial r} \right) + e_s n_s (E_\theta u_{s\theta} + E_\phi u_{s\phi}) - \sum_{s'} v_{ss'}^{\text{CT}} n_s (T_s - T_{s'}) - v_s^{\text{LT}} n_s T_s + P_s^{\text{H}}$$

Model Equation (2)

- **Neutral Transport**

$$\frac{\partial n_0}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} \left(-r D_0 \frac{\partial n_0}{\partial r} \right) + S_0$$

- **Maxwell equations**

$$\frac{1}{r} \frac{\partial}{\partial r} (r E_r) = \frac{1}{\epsilon_0} \sum_s e_s n_s$$

$$\frac{\partial B_\theta}{\partial t} = \frac{\partial E_\phi}{\partial r},$$

$$\frac{1}{c^2} \frac{\partial E_\phi}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (r B_\theta) - \mu_0 \sum_s n_s e_s u_{s\phi}$$

$$\frac{\partial B_\phi}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} (r E_\phi)$$

$$\frac{1}{c^2} \frac{\partial E_\theta}{\partial t} = -\frac{\partial}{\partial r} B_\phi - \mu_0 \sum_s n_s e_s u_{s\theta},$$

Transport Model (1)

- **Neoclassical transport**

- Viscosity force arises when plasma rotates in the poloidal direction.
- Banana-Plateau regime

$$F_{s\theta}^{\text{NC}} = - \sqrt{\pi} q^2 n_s m_s \frac{v_{Ts}}{qR} \frac{v_s^*}{1 + \nu_s^*} u_{s\theta}$$
$$\nu_s^* \equiv \frac{\nu_s q R}{\epsilon^{3/2} v_{Ts}}$$

- **This poloidal viscosity force induces**

- Neoclassical radial diffusion
- Neoclassical resistivity
- Bootstrap current
- Ware pinch

Transport Model (2)

- **Turbulent Diffusion**

- Poloidal momentum exchange between electron and ion through the turbulent electric field
- Ambipolar flux (electron flux = ion flux)

$$F_{i\theta}^W = - F_{e\theta}^W$$

$$= - ZeB_\phi n_i D_i \left[-\frac{1}{n_i} \frac{dn_i}{dr} + \frac{Ze}{T_i} E_r - \left\langle \frac{\omega}{m} \right\rangle \frac{ZeB_\phi}{T_i} - \left(\frac{\mu_i}{D_i} - \frac{1}{2} \right) \frac{1}{T_i} \frac{dT_i}{dr} \right]$$

- **Perpendicular viscosity**

- Non-ambipolar flux (electron flux \neq ion flux): $\mu_s = \text{constant} \times D$

- **Diffusion coefficient** (proportional to $|E|^2$)

- Current-diffusive ballooning mode turbulence model

Modeling of Scrape-Off Layer Plasma

- **Particle, momentum and heat losses along the field line**

- Decay time

$$\nu_L = \begin{cases} 0 & (0 < r < a) \\ \frac{C_s}{2\pi r R \{1 + \log[1 + 0.05/(r - a)]\}} & (a < r < b) \end{cases}$$

- **Electron source term**

$$S_e = n_0 \langle \sigma_{\text{ion}} \nu \rangle n_e - \nu_L (n_e - n_{e,\text{div}})$$

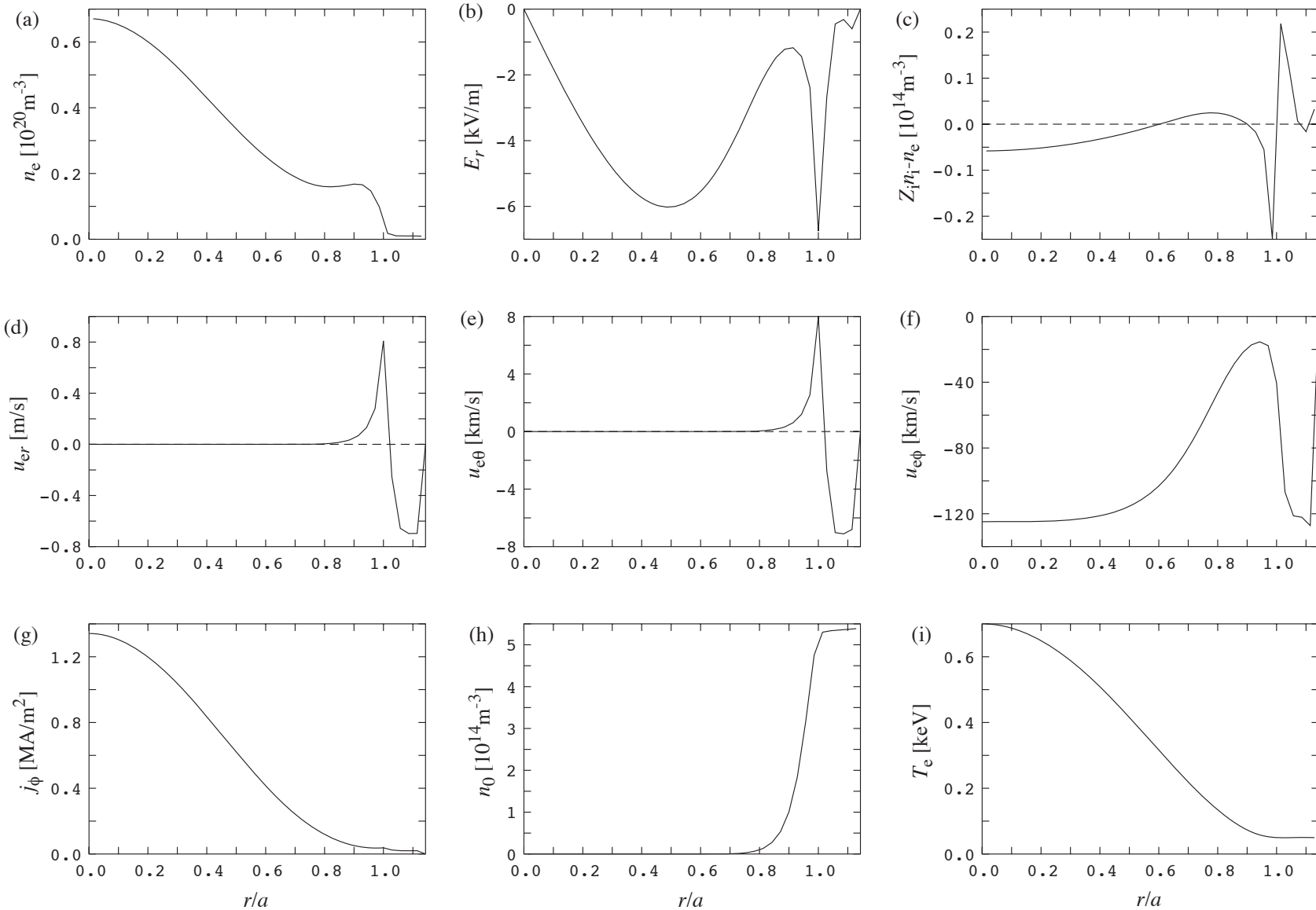
- **Recycling from divertor**

- Recycling rate: $\gamma_0 = 0.8$
- Neutral source

$$S_0 = \frac{\gamma_0}{Z_i} \nu_L (n_e - n_{e,\text{div}}) - \frac{1}{Z_i} n_0 \langle \sigma_{\text{ion}} \nu \rangle n_e + \frac{P_b}{E_b}$$

- **Gas puff from wall**

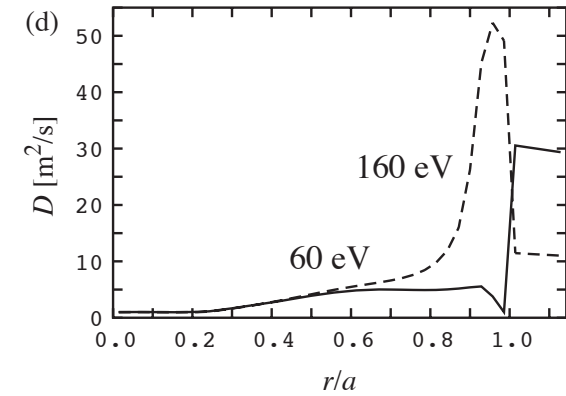
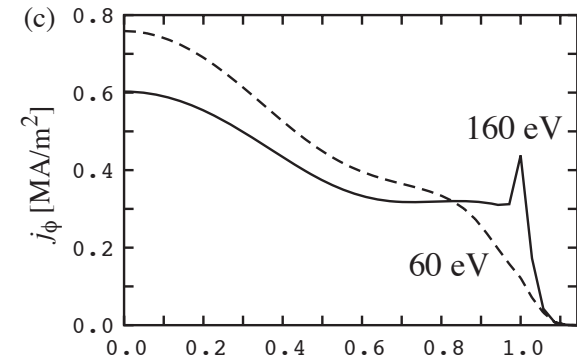
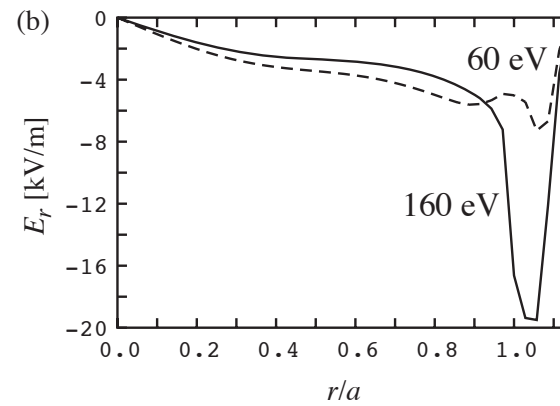
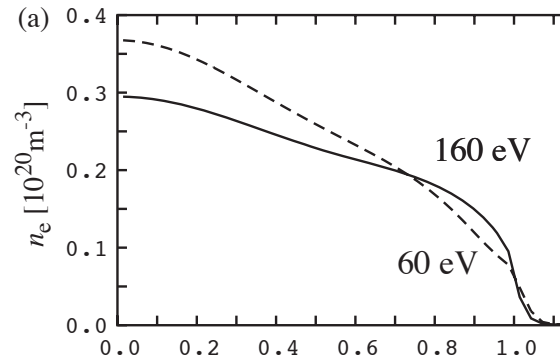
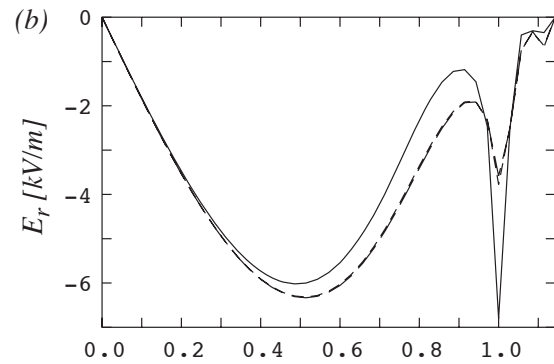
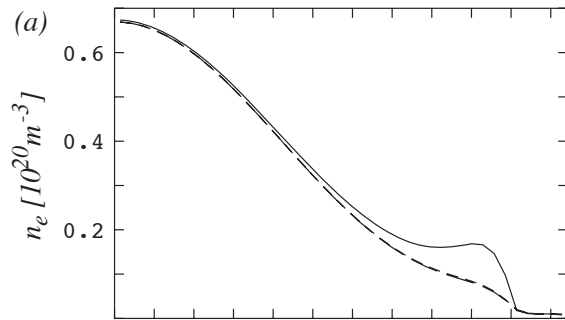
Typical Profiles without Turbulent Transport



Typical Profiles

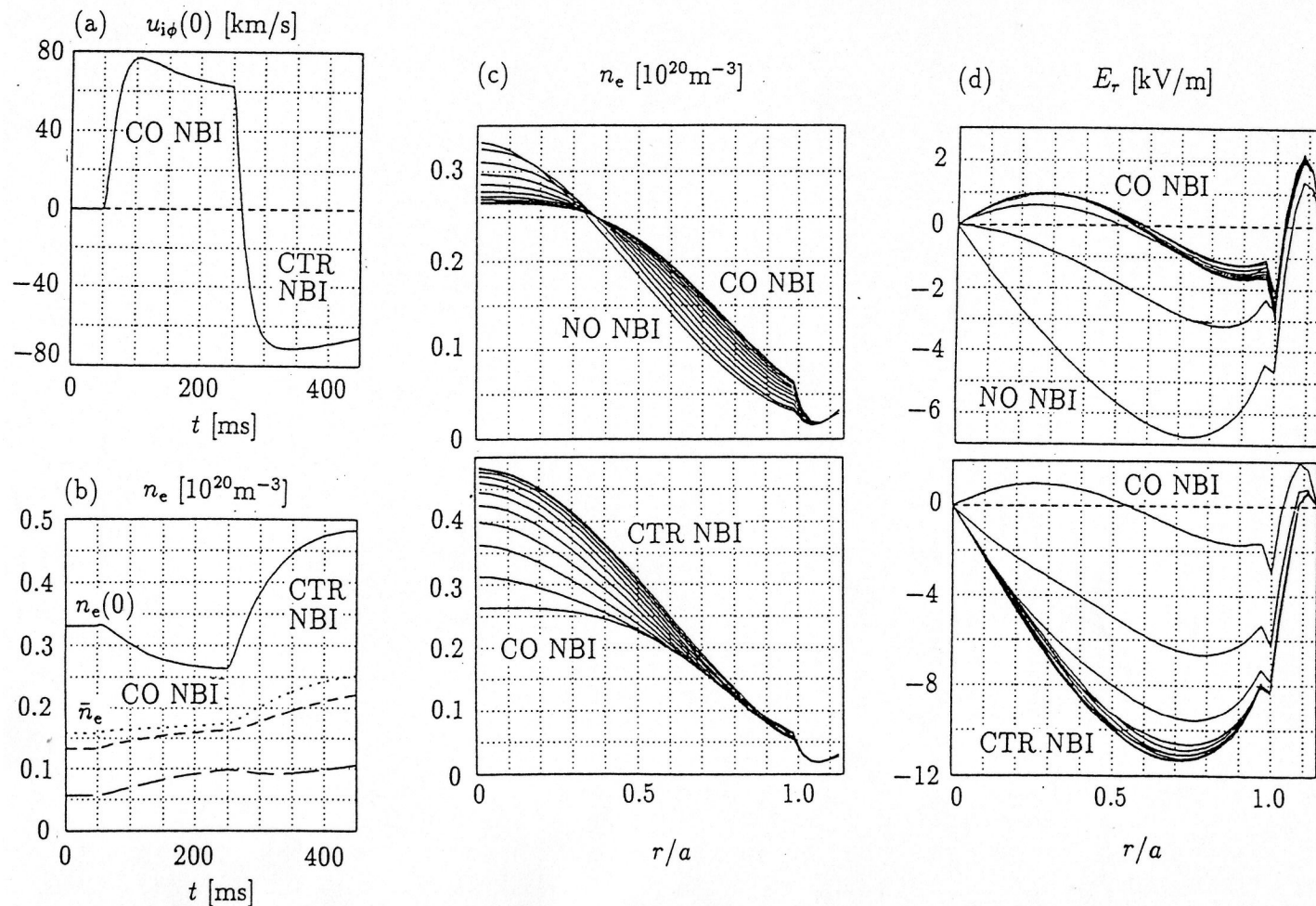
$$D_{TB} = 0$$

Edge Temperature Dependence



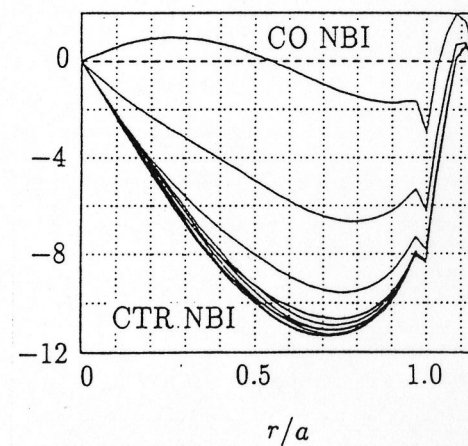
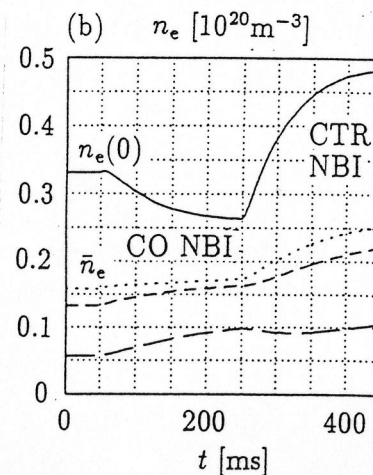
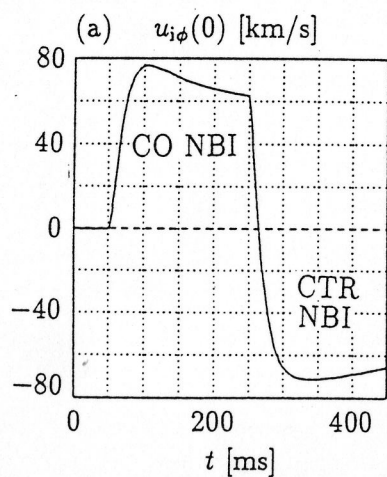
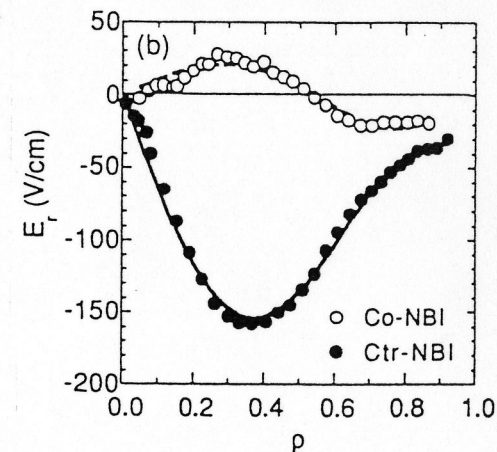
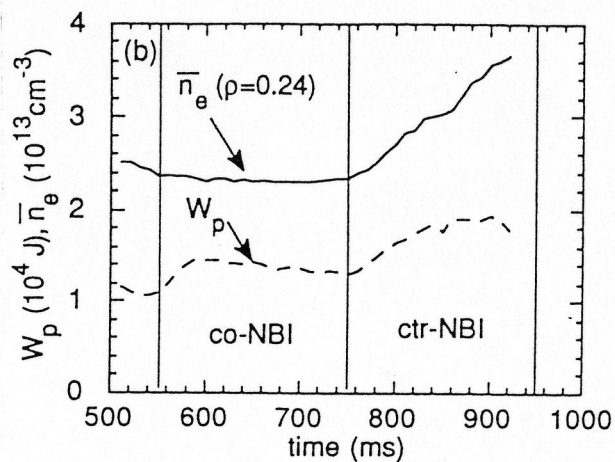
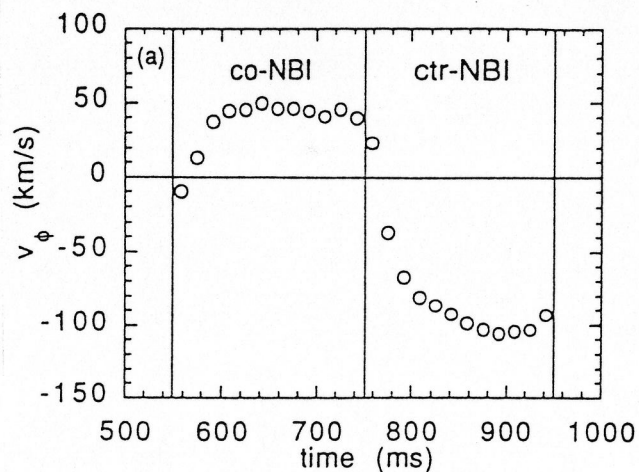
Simulation of plasma rotation and radial electric field

- **JFT-2M parameter**: NBI co-injection \longrightarrow counter-injection
- Toroidal rotation \implies Negative $E_r \implies$ Density peaking
- **TASK/TX**: Particle Diffusivity: $0.3 \text{ m}^2/\text{s}$, Ion viscosity: $10 \text{ m}^2/\text{s}$



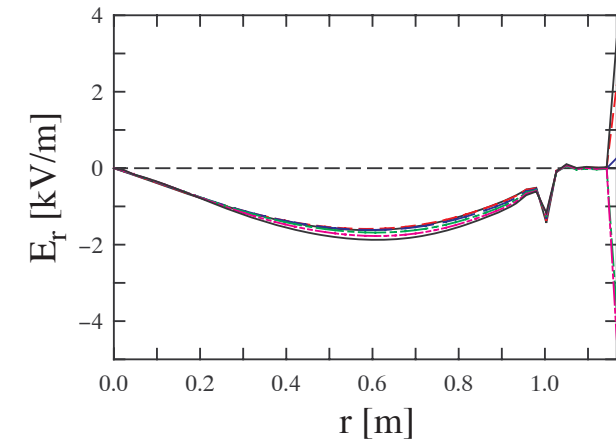
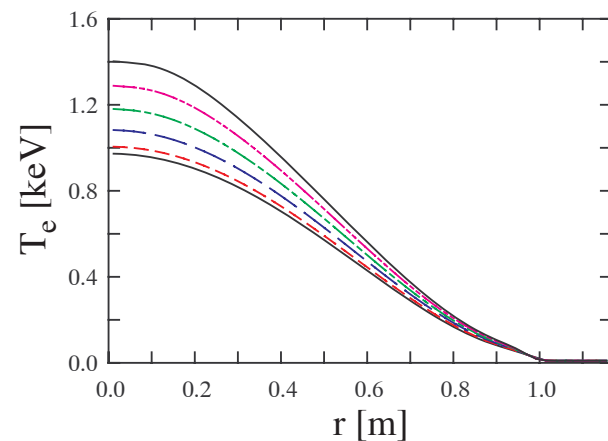
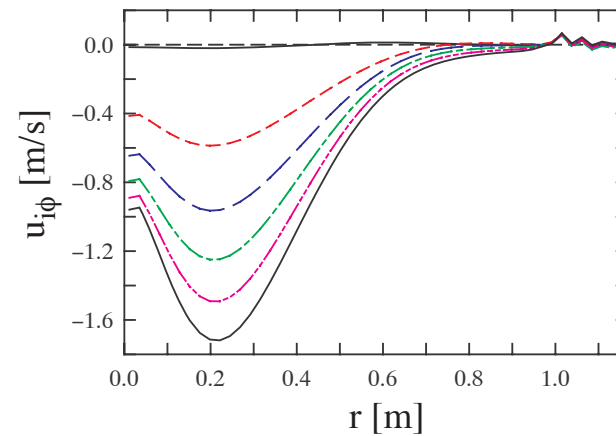
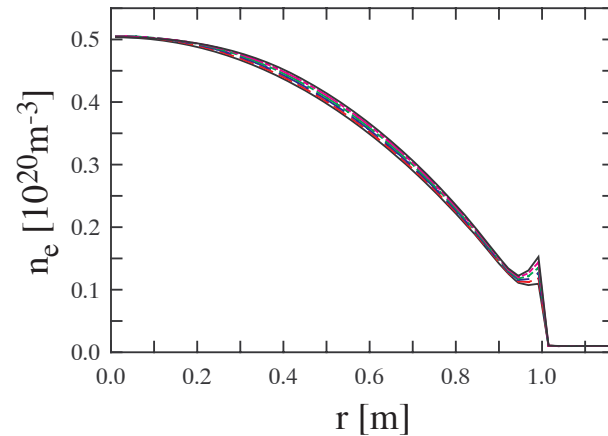
Comparison with JFT-2M Experiment

- **JFT-2M Experiment: Ida et al.: Phys. Rev. Lett. 68 (1992) 182**
- Good agreement with experimental observation



Transport Modeling in Helical Plasma

- **Neoclassical toroidal viscosity**
- **Negative magnetic shear**
- **Preliminary Result**
 - **NBI heating** ($P = 5$ MW) : Order of magnitude slower rotation



TASK2005 (Documentation)

1. **Introduction**
2. **TASK code** (Modular structure, How to get, install, and use)
3. **EQ: Equilibrium** **JAERI Rep 2004a+ α**
4. **TR: Transport** **JAERI Rep 2004a**
5. **DP: Wave Dispersion Relation** **Lecture note**
6. **WR: Ray and Beam Tracing** **JAERI Rep 2003a**
7. **WM: Full Wave Analysis** **JAERI Rep 2002b**
8. **FP: Momentum Distribution Function** **JAERI Rep 2003a**
9. **PL: Data Interface**
10. **Integrated Simulation**
11. **Works in Progress**
12. **Appendix: GSAF: Graphic Library**

Contents

1	Introduction	1
2	TASK code	2
2.1	Features	2
2.2	How to get TASK?	2
2.3	How to install TASK?	2
2.4	How to use TASK?	2
3	EQ: Equilibrium	3
3.1	Magnetic flux coordinates	3
3.1.1	Magnetohydrodynamics	3
3.1.2	Plasma equilibrium	3
3.1.3	Magnetic surface	3
3.1.4	Flux coordinates	3
3.1.5	Flux average	3
3.2	Axisymmetric equilibrium	3
3.2.1	Grad-Shafranov equation	3
3.2.2	Equilibrium for given current profile	3
3.2.3	Effect of toroidal rotation	3
3.3	Numerical scheme	3
3.4	Input parameters	3
3.5	Typical results	3
4	TR: Transport	4
4.1	Transport equation	4
4.1.1	Multi-fluid equation	4
4.1.2	Flux-Gradient relation	4
4.1.3	Magnetic diffusion	4
4.1.4	Diffusive transport equation	4
4.2	Transport model	4
4.2.1	Neoclassical transport model	4
4.2.2	CDBM transport model	4
4.2.3	ITG transport model	4
4.2.4	Other transport models	4
4.3	Sources and Sinks	4
4.3.1	Particle sources and sinks	4
4.3.2	Momentum sources and sinks	4
4.3.3	Energy sources and sinks	4
4.4	Constraints	4
4.4.1	Effects of MHD events	4

4.4.2	Boundary conditions	4
4.5	Numerical scheme	4
4.6	Input parameters	4
4.7	Typical results	4
5	DP: Wave Dispersion Relation	5
5.1	Dielectric tensor	5
5.1.1	MHD model	5
5.1.2	Cold plasma model	5
5.1.3	Warm plasma model	5
5.1.4	Kinetic plasma model	5
5.1.5	Gyro-kinetic plasma model	5
5.1.6	Relativistic effects	5
5.2	Dispersion relation	5
5.2.1	Cold plasma waves	5
5.2.2	Hot plasma waves	5
5.3	Numerical scheme	5
5.4	Input parameters	5
5.5	Typical results	5
6	WR: Ray and Beam Tracing	6
6.1	Ray tracing method	6
6.1.1	Ray tracing equation	6
6.1.2	Energy transport	6
6.2	Beam tracing method	6
6.2.1	Beam propagation	6
6.2.2	Beam tracing equation	6
6.3	Numerical scheme	6
6.4	Input parameters	6
6.5	Typical results	6
7	WM: Full Wave Analysis	7
7.1	Maxwell's equation	7
7.1.1	Magnetic flux coordinates	7
7.1.2	Local dielectric tensor	7
7.1.3	Wave equation	7
7.2	Eigenmode analysis	7
7.3	Numerical scheme	7
7.4	Input parameters	7
7.5	Typical results	7
8	FP: Momentum Distribution Function	8
8.1	Fokker-Planck equation	8
8.1.1	Coulomb collision term	8
8.1.2	Quasilinear wave-interaction term	8
8.1.3	DC electric field term	8
8.1.4	Radial transport term	8
8.2	Bounce average	8
8.2.1	Particle orbit	8
8.2.2	Bounce-averaged Fokker-Planck equation	8
8.3	Numerical scheme	8

8.4	Input parameters	8
8.5	Typical results	8
9	PL: Data Interface	9
9.1	Common data set	9
9.1.1	Device data	9
9.1.2	Quasi-static field data	9
9.1.3	Fluid plasma data	9
9.1.4	Kinetic plasma data	9
9.1.5	Equilibrium data	9
9.1.6	Dielectric tensor data	9
9.1.7	Wave field data	9
9.1.8	Transport data	9
9.2	Data exchange interface	9
9.3	Experimantal data access	9
9.4	Simulation data access	9
10	Integrated Simulation	10
10.1	Module control interface	10
10.2	Typical operation scenario	10
10.2.1	Ion cyclotron heating	10
10.2.2	Electron cyclotron current drive	10
10.2.3	Full current-drive burnig plasma	10
11	Works in Progress	11
A	GSAF: Graphic Library	12

Summary

- CDBM transport model reproduces various kinds of improved confinement modes associated with **ITB formation**.
- **ETB formation** in H-mode was studied by using surface-averaged fluid equations in both core and SOL plasmas. The change of transport mechanism across the separatrix generates the radial electric field at the edge and suppress the transport.
- In **toroidal helical plasmas**, neoclassical toroidal viscosity impedes toroidal rotation and affects the transport. Preliminary result was presented.
- **Further improvement in transport modeling is required:**
 - Turbulent transport model (zonal flow, E_r , ballooning mode)
 - Dynamical transport equations (numerical stability)
 - Coupling with SOL plasmas (open-field structure)